

CHAPTER 6

MUD ENGINEERING

This chapter covers the following items

- Function of drilling mud
- Drilling mud
- Types of drilling mud
 - Water base mud
 - Oil base mud
 - Emulsion mud
- Fundamental properties of mud
- Mud calculations
- Mud contaminant
- Mud conditioning equipment

Function of drilling mud

Cool bit and its teeth

- Drilling action requires mechanical energy in form of weight on bit, rotation and hydraulic energy
- Large part of energy dissipated as heat
- Heat must be removed to allow drilling
- Mud helps remove heat
- Mud helps remove cutting between the teeth and prevent bit balling

Cool and lubricate drill string

- Rotating drill string generates heat
- Mud help dissipate heat from hole
- Mud absorbs heat by convection and release it by radiation
- Mud lubricate drill string and reduce friction

Control formation pressure

- For safe drilling, high formation pressures must be contained within the hole to prevent damage and injury
- This achieved by hydrostatic pressure of mud

- Mud pressure should be higher than formation pressure
- An overbalance of 100-200 psi is used
- Pressure overbalance is referred as chip hold down pressure (CHDP)
- Penetration rate decreases as CHDP increases
- For abnormal pressure CHDP becomes negative and kick will happen

Carry cutting to surface

- Cutting generated by the bit must be removed
- Drilling mud carries cutting from bottom to surface
- Carrying capacity depends on annular velocity, plastic viscosity and yield point of mud and slip velocity of generated cutting
- For power law fluid, slip velocity is:

$$V_s = \frac{175 D_p (\rho_p - \rho_m)^{0.667}}{\rho_m^{0.333} \mu_e^{0.333}} \text{ ft/min}$$

$$V_s = \frac{15.23 D_p (\rho_p - \rho_m)^{0.667}}{\rho_m^{0.333} \mu_e^{0.333}} \text{ m/s}$$

D_p = Particle diameter, in or mm

ρ_p = Particle density, ppg, g/l

ρ_m = Mud density, ppg, g/l

μ_e = Effective viscosity, cp

- Annular velocity V_r is the flow rate divided by the annular area
- Lift velocity $V = V_r - V_s$
- The mud also must suspend cutting when drilling stops

Stabilize the wellbore

- Good mud cake stabilizes the hole
- Differential pressure between mud and formation keeps hole stable

- Reduce drilling time also help keep hole stable

Help in evaluation and interpretation of well logs

- During logging mud fill the hole
- Logs used to detect hydrocarbon, measure porosity, formation pressure
- Mud should posses properties that help evaluate these properties

Drilling mud

- Fresh water gives a pressure gradient of 0.433 psi/ft
- Normal formation pressure gradient is 0.465 psi/ft
- Fresh water can not control formation pressure
- Solids are added to increase water density to control pressure

Types of drilling mud

Water base mud

- Consists of:
 - Liquid water, continuous phase
 - Reactive solids, for viscosity and yield point
 - Inert solids, for density
 - Chemical additives, to control properties

Reactive solids

- Clays are added to provide viscosity and yield strength
- Mechanism is very complex
- Internal structure of clay particles and electrostatic forces develop viscosity
- Two types of clay are available
- Bentonite clay, montmorillomite (smectite) group used with fresh water
- Attapulgite clay, salt gel (playgorskite) group of clay used in fresh and salt water

Nature of clay

- Defines as natural, earthy, fine-grained material that develop plasticity when wet
- Form from chemical weathering of igneous and metamorphic rocks

- Mainly form from volcanic ash
- Wyoming bentonite is the famous one
- Atoms from layers
- There are three atomic layers: tetrahedral layer, octahedral layer, and exchangeable layer
- Tetrahedra made up of flat honeycomb sheet made up of silicon atom surrounded by four oxygen
- Tetrahedra are linked to form sheet by sharing three of their oxygen atoms
- Octahedral layer are sheets composed of linked octahedra, each made up of an aluminium or magnesium atom surrounded by six oxygen
- They linked through oxygen making three octahedra
- Exchangeable layers of atoms or molecules bound loosely into the structure giving the clay its physical properties
- The nature of these layers are stacked together on top of one another define the type of clay
- The sandwiches of tetrahedral and octahedral layers are joined with exchangeable layer
- Distance between layers are 9-15 Angstrom units (0.9-1.5 nm)
- In some clays, the exchangeable layer is relatively tightly bound in the structure
- Cation exchange capacity (CEC) measures how readily exchange take place
- CEC measured by dispersing a known amount of clay in a solution of magnesium chloride to replace as much as possible the exchangeable layer with magnesium
- It then transferred to a solution of potassium or calcium chloride
- The amount of potassium or calcium absorbed by clay is measured
- The amount is expressed in milliequivalents per 100 gm of dry clay and called (CEC)
- Typical values of bentonite are 70-130 and for attapulgite 5-99
- CEC used as a guide to the quality of clay

Hydration of clay

- Clays with high CEC exchange large amount of water into the exchangeable layer and adsorb water onto the outer surface of plates

- This effect gives high viscosity and high yield point
- Adsorption of water causes a very sticking expansion of clay
- For sodium bentonite, the distance between layers increased from 9.8 to 40 Angstrom
- For calcium bentonite from 12.1 to 17 A
- Overall hydration transform clay from dry power to plastic slurry
- The effectiveness is measured by yield of clay
- Yield of clay is defined as the number of barrels of 15 CP mud obtained from 1 ton (2000 lb) of dry clay
- Clay yield depends on: purity, nature of atoms in exchangeable layers and salinity of water

Bentonite and attapulgite

- Bentonite consists primarily of montmorillonite
- Came from French town Montmorillon, where first mined 1874
- Basic structure is close to pyrophyllite.
- There are a small number of exchangeable ions, sodium calcium and magnesium
- Most common bentonite are those with sodium and calcium as exchangeable ions
- Attapulgite belongs to a different family of clay minerals
- Instead crystallizing as platy crystals, it forms needle like crystals
- Have excellent viscosity and yield strength when mixed with salt water
- Disadvantage is suffering high water loss and poor sealing properties
- Dispersion, flocculation and deflocculation
- Agitating of clay suspension in water gives three modes: edge to edge; face to edge; and face to face
- Dispersion occurs with no face or edge association
- It results in increase in viscosity and gel strength
- Aggregate occurs with face to face association
- Aggregate results in a decrease in viscosity and gel strength
- Flocculation occurs with face to edge association
- It causes excessive gelation
- Flocculation can be broken by chemical thinners
- The resulting suspension is called deflocculated

Inert solids

- Include low gravity and high gravity
- Low gravity include sand and chert
- High gravity are added to increase mud weight or density
- Referred to as weighting materials
- Mud named as weighted mud, they are:

Barite (barium sulphate, BaSO_4) sp.gr. 4.2

- Used to prepare mud in excess of 10 ppg
- Referred to as weighting agent for low cost and high purity

Lead sulphides (galena) sp.gr. 6.5-7.0

- Allowing mud weight up to 35 ppg

Iron ores, sp. gr. 5+

- More erosive
- Contain toxic materials

Chemical Additives

- Used to control mud properties
- Divided into thinners and thickeners

Mud thinners

- Reduce viscosity by breaking attachment of plate through edge or face by attaching the clay plates
- **Phosphates:** sodium tertaphosphates ($\text{Na}_4\text{P}_3\text{O}_7$) and sodium acid pyrophosphated ($\text{Ba}_2\text{H}_2\text{P}_3\text{O}_7$), Suitable for any pH value, Limited to 175 F (70 C)
- **Chrome lignosulphonate:** Decomposes at 300 F (149 C), deflocculate and disperses clay, Reduce viscosity, yield strength and water loss, chrome lignosulphonate attaches to broken edges of clay reduces the attractive forces,
- **Lignite:** Decompose at 350 F (177 C), can be used as water loss agent

- **Surfactants** (surface tension reducing agent): Reduce water loss, Used as emulsifiers in oil base mud

Mud thickeners

- **Lime or cement:** Increase viscosity by flocculation resulting from replacement of Na^+ cations by Ca^{++} cations
- **Polymers :**
 - Large molecules made up of many repeated small units called monomers
 - Used for filtration control, viscosity modification, flocculation and shale stabilization
 - Cause little change in solid contents of mud
 - Polymer mud have high shear- thinning ability at high shear rate
 - This reduces viscosity and in turn frictional pressure loss
 - Hydraulic bit horse power increases and in turn penetration rates
 - Three types are available:
 - **Extenders:** sodium polyacrylate, increases viscosity by flocculating bentonite
 - **Colloidal polymer:** CMC, HEC and starch
 - **CMC:** an ionic polymer produced by treating cellulose with caustic soda and monochloro acetate, molecular weight ranges between 50,000 and 400,000
 - **HEC:** similar to CMC but hydrate in all types of salt waters
 - **Starch:** produced from corn or potatoes, molecular weight up to 100,000, used to develop viscosity and act as filtration control agent
 - Control filtration by forming sponge like bags wedges into the opening of the filter cake, disadvantage is that it is amenable to bacterial attack at low pH
 - **Large chain polymer:** include xanthenes gum
 - It is water soluble
 - Produced by the action of bacteria on carbohydrates

- Molecular weight 5,000,000
- Amenable of bacterial attack at temperature above 300 F
- Build viscosity in all types of water
- More expensive
- Limited with 13 ppg mud

Types of water base mud

Clear water

- Fresh or saturated brine water can be used to drill hard, compacted and near-normally pressured formation

Native mud

- Water pumped down letting it react with formation containing clay or shale
- Water dissolves clay and return to surface as mud
- Characterize by high solid content and high filter loss resulting in thick filter cake

Calcium mud

- Reduce clay and shale swelling
- Superior to fresh water mud for drilling gypsum and anhydrite
- Compared to sodium, calcium cations strongly attaches to clay sheets
- The sheets tend to be pulled together and aggregated
- Calcium reduces clay swelling by 50% with 150 ppm concentration, therefore clay cuttings will be reduced
- Can tolerate high concentration of drilled solids with viscosity increase
- Two types are available: Lime mud and gyp mud
- **Lime mud:** up to 120 ppm soluble calcium
 - Prepared by mixing bentonite, lime ($\text{Ca}(\text{OH})_2$), thinner, caustic soda and an organic filtration control agent
 - Lime provide the inhibiting ion (Ca^{++})
- **Gyp mud:** up to 1200 ppm soluble calcium
 - Similar to lime except that lime is replaced by gyp
 - Has greater stability than lime

Lignosulphonate mud

- Suitable for high density, > 14 ppg
- Work under high temperature 250-300 F (121-149 C)
- High tolerance for contamination of drilled solids, salt anhydrite, cement
- Low filter loss
- Consists of: Fresh or sea water, bentonite, chrome or ferrochrome lignosulphonate, caustic soda CMC or stabilized starch
- Optional materials such as lignite, oil, lubricants, surfactants
- **Not** Suitable for drilling shale
- Disadvantage; cause damage to reservoir permeability
- Now seldom used

KCl/Polymer muds

- Consists of: fresh or sea water; KCl; inhibiting polymer; viscosity building polymer (xanthenes); CMC or stabilized starch; caustic soda or caustic potash, and lubricants
- Suitable for drilling shale because it prevents shale sloughing
- Used to drill pay zone due to its low solid contents
- Known as low solid or nondisperssed mud
- Low tolerance to solids; need efficient desanders and desilters
- Have many advantages:
 - High shear thinning allow solids removal
 - High true yield strength
 - Improve bore hole stability
 - Good bit hydraulics
- Disadvantage is instability at temperature above 250 F (121 C)

Salt-saturated mud

- Water is saturated with sodium chloride; 315,000 ppm
- Drills salt domes and salt sections, prevent hole washout
- Used with polymer to inhibit the swelling of bentonitic shale
- Consists of: fresh, brine or sea water; common salt; encapsulating polymer, and CMC or starch
- Low tolerance to solids
- Need high filter loss additives

Oil base mud

- Water in oil emulsion
- Diesel or crude oil forms its continuous phase
- Sometimes called invert emulsion
- Water droplets are emulsified in oil
- Water is used for gel strength and barite content
- Soaps are used as emulsifiers
- Soaps are made from monovalent ion (Na^+) or divalent ion (Ca^{++})
- The soap molecule bridge together oil and water interfaces
- Agitation is required to break the water into small droplets
- Oil/water ratio determine the final properties
- Higher oil water **ratio** increases resistance to contamination and temperature stability
- Used to drill hole with severe stability
- More stable at high temperature
- An excellent to drill pay zone; reduce formation damage and preserve original permeability
- Disadvantages:
 - Contaminate the environment
 - Flammability hazards
 - Difficult removal of drilled solids due to high plastic PV
 - Difficult electric logging

Emulsion mud

- Water is a continuous (normal oil 5-10% by volume)
- Formulated by using sodium soap as emulsifier
- Oil is added to increase penetration rate, reduce filter loss, improve lubricity, reduce lost circulation and reduce torque and drag in directional well

Properties of mud

- Include weight or density, rheological properties, filtrate and mud cake, and pH value

Mud weight or density

- Weight or mass per unit volume
- Depend on solids in the liquid, either in solution **or** suspended

- Calculated by sum of weighs over sum of volumes
- Increases by adding solid materials
- Decreased by adding water or oil or aerating the liquid
- Measured by mud balance: a steel cup filled with freshly mud sample and balanced on a knife edge
- Expressed in ppg, pcf or kg/m³

Rheological properties

- They are plastic viscosity, yield point and gel strength

Plastic Viscosity (PV)

- Control the magnitude of shear stress develops as one layer of fluid slides over another
- Measure of friction between layers
- Provides a scale of the fluid thickness
- Decreases with increasing temperature for liquids; and the reverse with gases
- Viscosity depends on fluid velocity and flow pattern (laminar or turbulent)
- Annular Effective Viscosity is difficult to measure, but calculated.
- For Bingham plastic model
- $$\mu_e = PV + \frac{300}{V_a} (D_h - D_p) YP$$
- For power law model
- $$\mu_e = \left[\frac{2.4 V_a (2n+1)}{(D_h - D_p) 3n} \right]^n 200K \left(\frac{D_h - D_p}{V_a} \right)$$
- Plastic viscosity and yield point are measured by Viscometer
- Six readings are available at six rpm (3, 6, 100, 200, 300, 600)
- PV is the difference between reading sat 600 and that at 300
- $PV = \theta_{600} - \theta_{300} \text{ cp}$
- YP is the difference between readings at 300 and PV
- $YP = \theta_{300} - PV = 2\theta_{300} - \theta_{600} \text{ lb/100 ft}$
- March funnel is used to measure static viscosity
- Measurement shows thickness or thinning of fluid. Provide early warnings of potential fluid problems.

- 1500 cc funnel with orifice at the end is filled with mud
- Time to collect 950 cc (one quart) is measured
- Time for water about 26 sec

Yield point

- A measure of the attractive forces between particles due to positive and negative charges
- Measure the forces causes mud to gel in case of motionless
- Directly affects the carrying capacity of mud
- Shows a minimum level of stress must be provided before mud flow
- Expressed in lb/100ft² (Example 6.1)

Gel strength

- Measure the ability of mud to develop gel structure
- Defines the ability of mud to hold solids in suspension and measure thixotropic properties of mud.
- Thixotropy is the ability of mud to develop a semi-solid structure when at rest.
- Determined using viscometer
- The sample stirred at high speed and then allowed to rest for 10 sec or 10 min
- The torque reading at 3 rpm is taken as gel strength at specified time.
- Expressed in lb/100 ft²
- Converted to metric by multiplying by 0.478

Filtration and filter cake

- Fluid loss against porous and permeable rock is called filter loss
- A layer of solids deposited on the rock is described as filter cake
- Loss occur when mud pressure is higher than formation pressure
- Quantity of mud loss depends on volume of filtrate and thickness and strength of filter cake, and differential pressure
- The initial volume of filtrate lost to the rock while the filter cake is forming is described as "spurt loss"
- Can be determined by filter press, called API filter press
- Consists of a cylinder with 3 in diameter and 2 1/2 in length with fine screen at the base cover with a filter paper
- Pressure applied on the sample, 100 or 500 psi and 60 F

- The volume collected in cc per 30 min, API filter loss
- The thickness of mud cake in 1/32 in express the mud cake thickness
- Bentonite, emulsified oil, dispersant, CMC and starch used to reduce filter loss, starch is used with pH > 11.5
- Ideal mud gives small filter loss and thin and tough mud cake

The pH of mud

- Describe the acidity or alkalinity of mud
- Defined as the negative logarithm of the hydrogen ion (H^+)
- Measured by pH meter
- $H^+ \cdot OH^- = 10^{-14}$
- The following table shows the pH value and the description of the fluid

H^+	OH^-	$pH = -\log H^+$	Description
10^0	10^{-14}	0	Acidic
10^{-7}	10^{-7}	7	Neutral
10^{-10}	10^{-4}	10	Basic
10^{-14}	10^0	14	Basic

The following table shows the pH value of some solutions

Solution	pH
Distilled water	7
Bentonite suspension	8
Caustic soda, 10% concentration	13.3
Lignite, 10%	5
Sodium acid phosphate	3.09- 4.2

- Play a major role in controlling calcium stability
- Starch is used to increase pH to 11.5, but with bactericide
- Optimum pH between 8 and 11
- Minimum value of 7 should be maintained to control corrosion

Mud calculations

Mud weight increase in Field Unit

- Amount of barite
- $M = 1491 \frac{(\rho_{m1} - \rho_{m2})}{(35.5 - \rho_{m2})}$ Lbs
- Number of sacks
- $S = 15.9 \frac{(\rho_{m2} - \rho_{m1})}{(35.5 - \rho_{m2})}$ Sacks
- Mud volume increase due to adding barite
- $V = \frac{42(\rho_{m2} - \rho_{m1})}{(35.5 - \rho_{m2})}$ bbl

To reduce mud weight by adding oil or water

- $V_{o,w} = V_{m1} \frac{(\rho_{m2} - \rho_{m1})}{(\rho_{o,w} - \rho_{m2})}$

Final mud density

- $\rho_{m3} = \rho_{m1} - \left(\frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$
- Or
- $\rho_{m3} = \rho_{m1} - \left(\frac{V_{m2}}{V_{m3}} \right) (\rho_{m1} - \rho_{m2})$

In Metric System

Mud weight increase

➤ Amount of barite

$$➤ M = 42500 \frac{(\rho_{m1} - \rho_{m2})}{(4250 - \rho_{m2})} \quad \text{Kg}$$

➤ Number of sacks

$$➤ S = 996.7 \frac{(\rho_{m2} - \rho_{m1})}{(4250 - \rho_{m2})} \quad \text{Sacks}$$

➤ Mud volume increase due to adding barite

$$➤ V = \frac{10(\rho_{m2} - \rho_{m1})}{(4250 - \rho_{m2})} \quad \text{m}^3$$

To reduce mud weight by adding oil or water

$$➤ V_{o,w} = V_{m1} \frac{(\rho_{m2} - \rho_{m1})}{(\rho_{o,w} - \rho_{m2})}$$

Final mud density

$$➤ \rho_{m3} = \rho_{m1} - \left(\frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$$

➤ Or

$$➤ \rho_{m3} = \rho_{m1} - \left(\frac{V_{m2}}{V_{m3}} \right) (\rho_{m1} - \rho_{m2})$$

Mud contaminants

Sodium chloride

- Enters mud during drilling salt domes, rock salt beds, evaporites or any bed containing salt water
- Increase viscosity, yield strength and gel strength of bentonite mud due to flocculation
- Salt decreases pH value
- Salt solution cause hole enlargement or even a complete washout, so salt saturated mud is recommended
- Routine measurements of mud chloride content are used to monitor the change in mud salinity
- Sudden increases indicates salt water flow
- Thinners used to reduce viscosity and filtration rate, caustic soda to increase pH values

Anhydrite and gypsum

- Forms mainly of calcium sulphate (CaSO_4)
- Formation containing anhydrite and gypsum are common in massive or interbedded sections
- Contamination leads to clay flocculation, increase viscosity, yield strength, filtrate loss and gel strength
- Caustic soda and chrome lignosulphonate are added to mud to drill these formation
- Sodium carbonate (Na_2CO_3) can added to treat mud by forming insoluble materials (CaCO_3)

Cement

- Enter mud from poor cement jobs or squeeze cementing
- Increase viscosity, yield point, pH, and gel strength
- Discard mud used to drill cement
- Mud contaminated with cement treated with sodium bicarbonate forming insoluble materials (CaCO_3)
- Calcium content should be below 200 ppm

Mud conditioning

- Mud prepared by mixing (water or oil) with (bentonite or attapulgite), barite and various chemicals
- Mud carries drilled cuttings to surface

- Mud lose much of its desired properties if drilled solids are not removed, and cause potential problems such as loss of circulation
- Mud conditioning equipment remove unwanted solids
- Three sections are available
 - Suction tank
 - Addition and mixing section
 - Removal section

The addition and mixing section

- Mixing operation involves pouring of mud solids or chemicals through a hopper connected to high shear jet
- The shear jet homogenize the mixture
- The resulting mud is again agitated with mud gun or an agitator
- The resulting mud is then directed to the suction tank
- The mud in the suction tank is handled with a centrifugal or charge pumps
- The charge pumps give the mud a pressure of 89 to 90 psi (5.5-6.2 bar) before it delivers to the main rig pump
- This improve the rig pump efficiency
- From the rig pump the mud flows through the circulation system

The removal section

- Consists of:
 - Shale shaker
 - Hydrocyclone
 - Mud cleaner
 - Centrifuge

Shale shaker

- A vibrating or rotating sieve
- Sieves have opening enough to pass mud and its solids
- Cuttings retained on the sieve and collected in a pit
- Can be single- or double-decker shaker
- Mud from shale shaker pass to sand trap below shale shaker
- Small drill cutting removed by gravity

Desander and desilter

- Mud from sand trap sent to desander and desilter (hydrocyclone)
- Centrifugal force separate solids from mud

- Hydrocyclones contain no moving parts
- Consists of:
 - An upper cylindrical section with a tangential feed tube and fitted with a vortex
 - A conical section ending with an apex
- Solids flow through the apex and discharged
- Clean mud flows through the vortex and send to the active pit
- Large size used for sandy particles (above 74 micron)
- Small-sized used for silty particles (2-74 micron)
- Desander diameter is from 6-12 in optimum 10 in
- Desilter diameter is from 4-5 in., not used with weighted mud

Mud cleaner

- Replaces desander and desilter for weighted mud
- Used to save barite
- Consists of a hydrocyclone with 4 in diameter above a high-energy vibrating screen with openings of 40-125 micron
- The barite will pass through the screen and reused
- Advantage is to save barite, KCl, oil and mud
- Waste is much drier and need fewer disposal problems

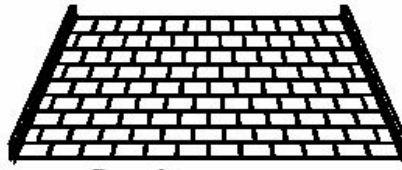
Centrifuges

- Use centrifugal forces
- Separate heavy solids from liquid and lighter component
- Consists of:
 - Horizontal conical steel bowl, rotating at high speed
 - Double screw type conveyor inside the bowl rotated at low speed
 - The conveyor contains a hollow spindle for feeding mud
- The solids removed from the liquid by centrifugal forces
- The rotation of the bowl holds the slurry in bond against the wall of the bowl
- The conveyor blades scrapes or pushes the settled solids towards a narrow end of the bowl
- The solids collected are a dump particles with no fluids
- The liquid and clay particles collected as an overflow from ports at the large end of the bowl
- Clean mud requires treatment if properties changed

Two-dimensional

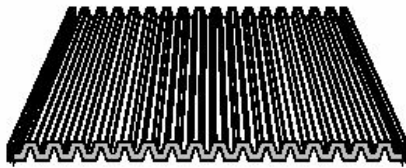


Two-layer nonperforated
plate panel

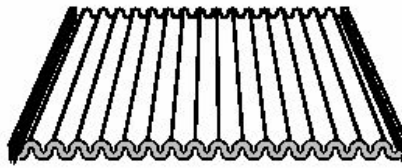


Panel type screen

Three-dimensional

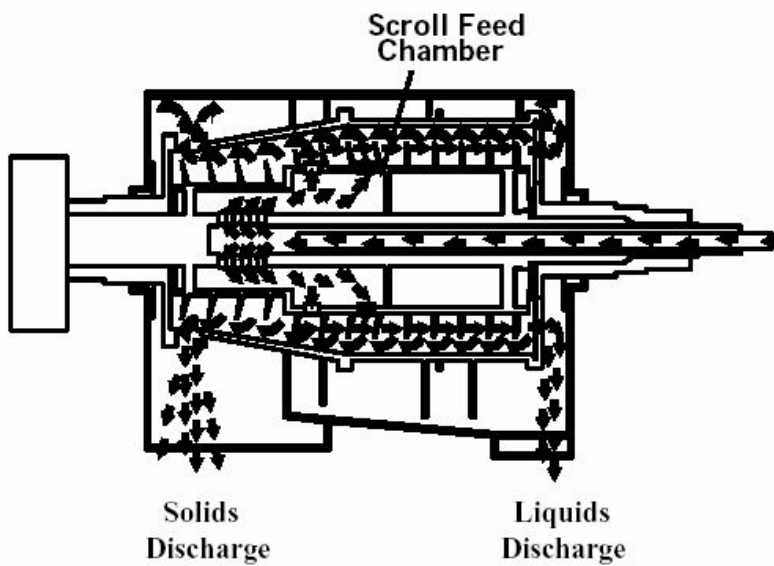


Plateau

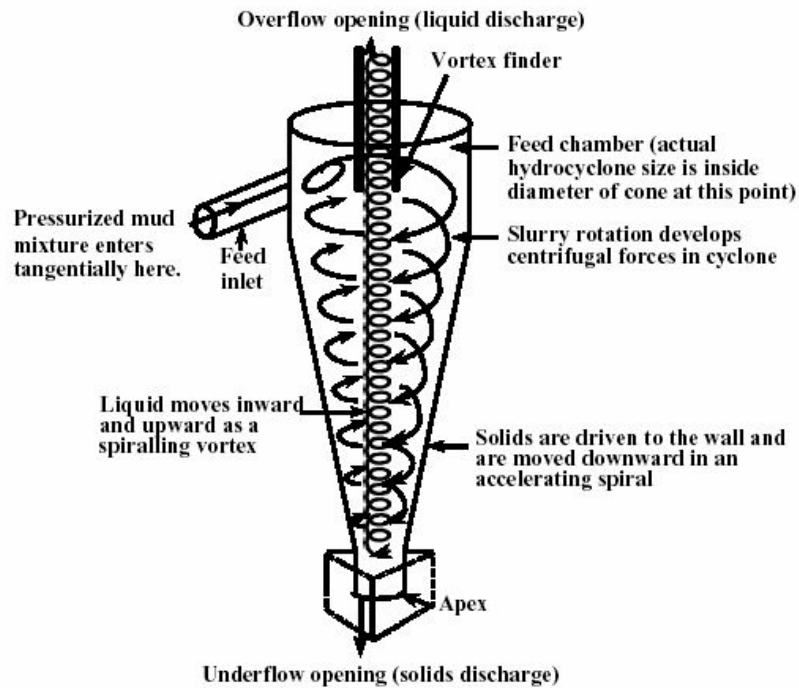


Pyramid

Decanting centrifuge cross-section



Hydrocyclone solids-removal process



Hydrocyclone operating ranges

Equivalent size cut removed (in microns)

